



Short communication

A high-efficiency coaxial pulse tube cryocooler with 500 W cooling capacity at 80 K

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ABSTRACT

High-temperature superconductivity power-grid technologies require a highly reliable and efficient cryocooler with cooling power of 100 W to kilowatt level at liquid-nitrogen temperatures to produce cryogenic environments. This paper describes the design of a coaxial Stirling-type pulse tube cryocooler to meet this need. In the designed cryocooler, the regenerator and pulse tube are lengthened to avoid possible temperature inhomogeneity. In an experiment, the azimuthal temperature difference at the middle of the regenerator was less than 30 K. With 7.6 kW electric power input, the cryocooler offers more than 520 W cooling power at 80 K corresponding to a relative Carnot efficiency of 18.2%. When the cooling power was less than 370 W, the efficiency is higher than 20%.

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1. Introduction

The demonstration of full-scale prototypes has brought high-temperature superconductivity (HTS) power-grid technologies to the point of commercialization. Such HTS devices generally work at liquid-nitrogen temperatures. Highly reliable, highly efficient and low-cost cryocoolers are needed to produce the cryogenic environments. Presently available cryogenic coolers include the evaporative cooler, the crank-type Stirling cryocooler, the Gifford–McMahon cryocooler and the Brayton cycle cooler [1]. However, these coolers are inefficient, inconvenient to use, short-lived, or yield a low specific power (cooling power per unit volume) [2].

The Stirling-type pulse tube cryocooler has been considered a promising candidate for cooling HTS devices. It has two main parts: a linear compressor and a cold finger. In the linear compressor, electric power is converted into acoustic power in the form of oscillating flow. There is less friction than in a conventional rotary valveless compressor. In the cold finger, acoustic power is consumed to produce a refrigeration effect without any moving parts. The combination of the two technologies provides a Stirling-type pulse tube cryocooler that promises high efficiency, high reliability and small size. In past decades, the Stirling-type pulse tube cryocooler was mainly developed for cooling infrared detectors

in aerospace and military applications. The reported overall relative Carnot efficiency at liquid-nitrogen temperatures was as high as 20% [3]. However, the cooling capacity is often less than 10 W. For application to an HTS power grid, the cooling capacity should be increased to the order of 100 W or kilowatts.

With increasing cooling capacity, the length-to-diameter ratio (L/D ratio) of the regenerator in a pulse tube cryocooler decreases. The regenerator looks more like a thin cake than a cylinder. Because of the great temperature gradient along the axis, the temperature distribution on the cross-section of the regenerator readily becomes inhomogeneous. The coupling of the temperature inhomogeneity and the flow admixes the working gas of different temperatures and deteriorates the cooling performance severely. Much effort has been made to suppress the temperature inhomogeneity in recent years. Besides straightening the flow at the two ends of the regenerator, inserting low-mesh copper screens to improve the radial heat conductivity of the regenerator is considered the most effective way to suppress the inhomogeneity [4,5]. However, the copper screens weaken the regenerative effect and induce additional heat loss along the axis. If too many copper screens are inserted, the cooling performance can even deteriorate [6].

Owing to the temperature inhomogeneity, it is difficult to improve the efficiency of high-capacity pulse tube cryocoolers. Generally, the relative Carnot efficiency is less than 15% [7,8]. The pulse tube cryocooler with the highest efficiency was reported by Zia. The cold finger of this cryocooler was designed in-line. The cryocooler offers 300 W of cooling power at 80 K corresponding to an efficiency of 19% [9]. In practice, it is more convenient to couple

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a co-axial cold finger with the load than to use the in-line design. However, the former approach further increases the ratio of the length to diameter and is thus seldom employed in high-capacity pulse tube cryocoolers [10]. This paper introduces a pulse tube cryocooler with a coaxial cold finger. The cryocooler offers 520 W of cooling power at 80 K corresponding to a relative Carnot efficiency of 18.2%.

2. Theoretical analysis

Perfect heat transfer between the working gas and the fillings in the regenerator is desired, which in turn requires that the hydraulic diameter of the fillings be much smaller than the gas thermal penetration depth. However, a smaller hydraulic diameter means high flow resistance. Therefore, the regenerator cannot be too long. In our previous study, overall relative Carnot efficiency (cooling power/ input electric power/Carnot efficiency) exceeding 20% was obtained with a 65 mm-long regenerator filled with 300-mesh stainless-steel screens [3]. Here, to enlarge the cooling capacity, the diameter of the regenerator should be at least 120 mm. If the length is kept the same, the L/D ratio is only about 0.52. Previous research has already showed that the ratio at this level makes it difficult for the temperature to be homogeneous [5,6].

To investigate the possibility of lengthening the regenerator, the influence of the regenerator's length on the efficiency is simulated according to thermoacoustic theory [11,12]. The results are shown in Fig. 1. To expel the influence of the pulse tube in this simulation, only the main heat exchanger, the regenerator and the cold heat exchanger are simulated as shown in Fig. 1. The regenerator is 120 mm in diameter filled with 300-mesh stainless-steel screens with porosity of 0.7. The temperatures of the cold and hot heat exchanger are 80 K and 293 K, respectively. The average pressure is 3 MPa and the working frequency is 50 Hz. The swept volume at the inlet of the hot heat exchanger is fixed as 170 cubic centimeter. The volume flow rate at the outlet of the cold heat exchanger is optimized to ensure maximum efficiency. It can be seen that the optimum length of the regenerator is about 60 mm. In the range near the optimum, the length of the regenerator does not affect the relative Carnot (cooling power/acoustic power delivered by the compression piston/Carnot efficiency) efficiency greatly. For example, if the regenerator is lengthened to 75 mm, the efficiency only decreases by 0.1. Meanwhile, the L/D ratio increases 25%. Therefore, 75 mm is chosen as the length of the regenerator in the experimental setup.

The flow in the pulse tube affects the temperature distribution in the regenerator, so the pulse tube should also be carefully designed. Fig. 2 shows the effect of the pulse tube length on the efficiency. In this simulation, the pulse tube is 60 mm in diameter.

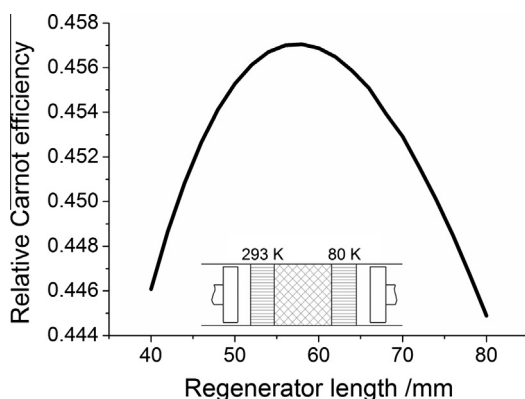


Fig. 1. Effect of the regenerator length on the efficiency.

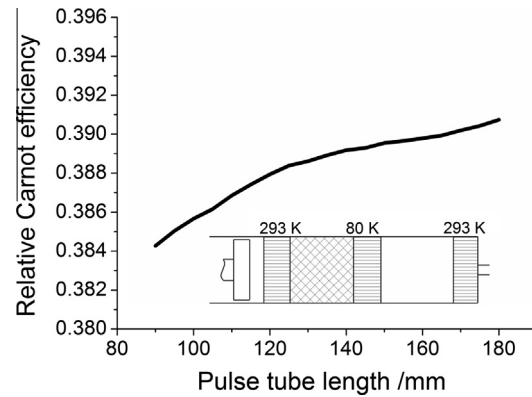


Fig. 2. Effect of the pulse tube length on the efficiency.

The impedance at the hot end of the pulse tube is optimized for maximum efficiency. Whether the impedance can be realized by an inertance tube is not taken into consideration. The other parameters are the same as those in the previous simulation. Obviously, the volume of the pulse tube does not affect the efficiency as long as the ideal impedance can be realized. With an increase in the pulse tube length, the efficiency could even be slightly higher because of the decrease in heat conduction along the pulse tube. What must be mentioned is that the ideal phase angle of the impedance should be larger for a longer pulse tube. If the length is 180 mm, the phase angle, the phase angle, by which the pressure leads the volume flow at the hot end, is 84° . It is not possible to realize such a large phase angle with an inertance tube in small pulse tube cryocoolers [13], so in such cryocoolers, the pulse tube is generally less than 90 mm. Fortunately, the cooling capacity in the considered pulse tube cryocooler is quite large and the phase angle can be realized with the inertance tube. For less temperature inhomogeneity and convenience in structure, the pulse tube is lengthened to 155 mm. The corresponding ideal phase angle of the impedance is 82° .

3. Experimental setup and results

The schematic of the experimental setup is shown in Fig. 3(a). The setup is mainly composed of a driver and a cold finger. The driver is a linear compressor with dual magnets moving in opposite directions. On the compression surface of the piston, there is a check valve. When the gas in the compression chamber is compressed in each cycle, a small portion of the gas flows into the internal reservoir of the piston and raises the average pressure in the internal reservoir above the pressure outside. The gas is then driven to the gap between the piston and cylinder through orifices to suspend the piston. By employing such gas bearings, the Oxford springs used in traditional linear compressors are eliminated. The cold finger is coaxial. The main parameters are presented in Table 1. The regenerator is only filled with 300 mesh stainless steel screens. Because hundreds of watts of acoustic power will be dissipated in the inertance tube, the inertance tube is also cooled by water. Four Pt-100 resistance thermometers (T1–T4 in Fig. 3) with an accuracy of ± 0.1 K are installed equidistantly around the cold heat exchanger. Another four (T5–T8 in Fig. 3) are installed on the circumference of the regenerator at half of its length to measure the azimuthal temperature distribution. Five constantan wires heated by a direct-voltage source are mounted on the cold tip to simulate the heating load. The voltage and current of the compressor are measured with a Tektronix P5200 High Voltage Differential Probe and Tektronix TCP303 Current Probe. The input electric power is calculated from the voltage and current data acquired through a

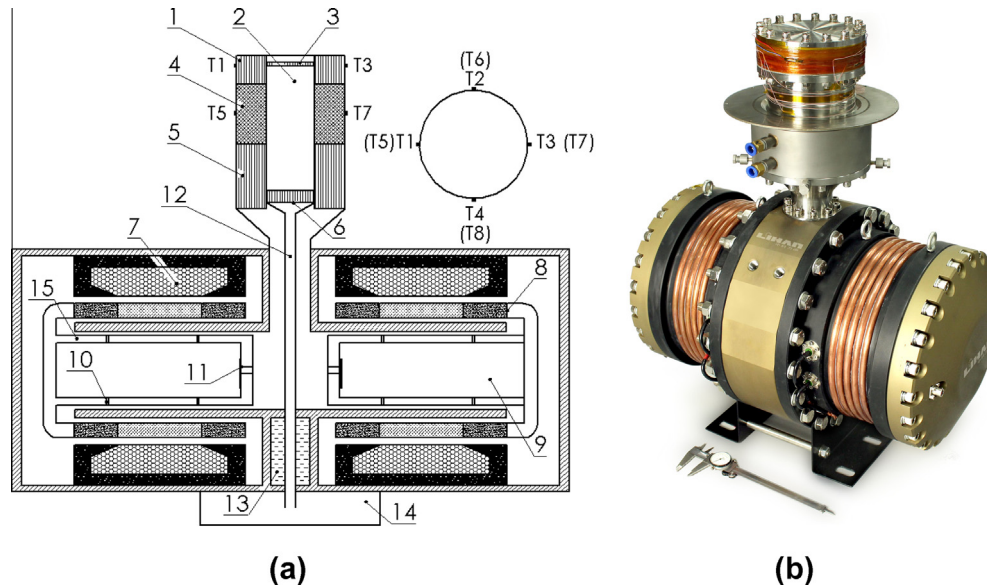


Fig. 3. (a) Schematic and (b) photograph of the pulse tube cryocooler, where 1 is the cold heat exchanger, 2 is the pulse tube, 3 is the flow straightener, 4 is the regenerator, 5 is the main heat exchanger, 6 is the secondary heat exchanger, 7 is the motor stator, 8 is the moving magnet, 9 is the reservoir in the piston, 10 is the orifice, 11 is the check valve, 12 is the inertance tube, 13 is the cooling water, 14 is the reservoir connected with the inertance tube, and 15 is the piston.

program based on Labview 7.1 of National Instruments Inc. Fig. 3(b) is a photograph of the compressor and the cold finger.

After primary experimental optimization, the charging pressure is adjusted to 2.7 MPa and the working frequency is set as 47 Hz. Fig. 4 presents the overall relative Carnot efficiency (cooling power/input electric power/Carnot efficiency) of the cryocooler with about 5 kW input electric power. The maximum temperature difference ΔT around the middle of the regenerator for each cooling temperature is also presented in the figure. In the range

from 80 to 120 K, the efficiency remains above 20%. It reaches a maximum of 21.6% at a cooling temperature of 100 K. At 60 K, the efficiency drops appreciably. This may be due to the mismatch between the inertance tube and cryocooler.

Fig. 5 shows the input electric power dependence of the cooling power and the relative Carnot efficiency at a cooling temperature of 80 K. With 3.6 kW electric power, the cooling power is 285 W, corresponding to relative Carnot efficiency of 20.9%. With an increase in input electric power, the temperature difference between the gas and wall in the main heat exchanger increases. When the input electric power is 7.6 kW, the gas temperature in the channel between the compressor and the cold finger could be as high as 70 °C. This may be one of the reason that the efficiency decreases monotonously in this figure.

Owing to the high thermal conductivity of copper, the temperature differences among the four thermometers on the cold heat exchanger are less than 2 K. The regenerator is not packed in any high thermal conductivity fillings, and the azimuthal temperature distribution at the middle of the regenerator was carefully measured. Fig. 6 shows the temperature of the four thermometers around the middle of the regenerator at a cold heat exchanger of 80 K. Here, no large temperature difference is observed. The

Table 1
Main parameters of the pulse tube cryocooler.

Diameter and length of regenerator	61 mm in inner diameter, 134.6 mm in outer diameter, 75 in length
Diameter and length of pulse tube	60 mm in diameter, 155 mm in length
Diameter and length of inertance tube	13 mm in diameter, 1.7 m in length
Volume of reservoir	4.5 l
Diameter and stroke limit of piston	118 mm, 28 mm peak-to-peak

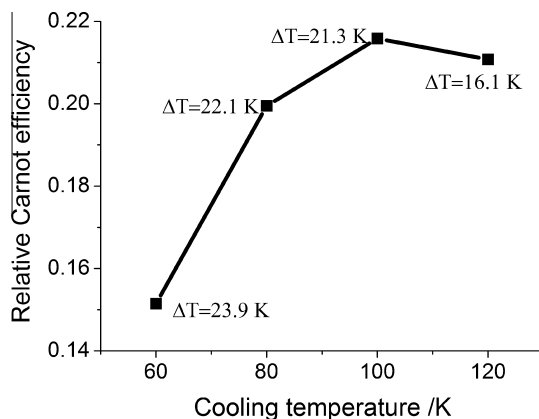


Fig. 4. Relative Carnot efficiency at different cooling temperatures.

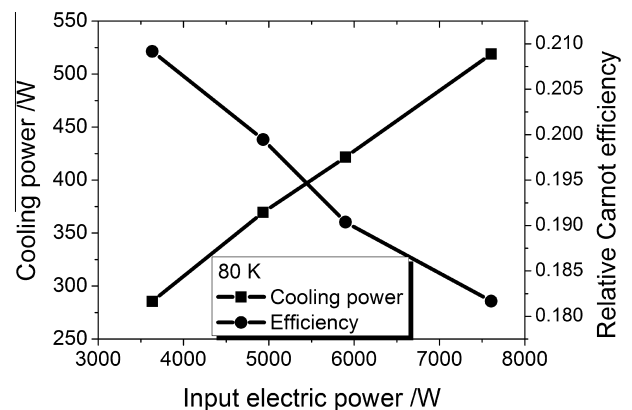


Fig. 5. Electric power dependence of the cooling power and efficiency.

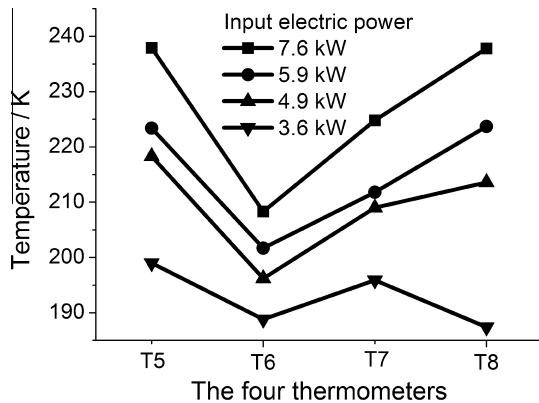


Fig. 6. Temperatures recorded by the four thermometers around the middle of the regenerator at a cold heat exchanger of 80 K.

maximum temperature difference is about 29.5 K with 7.6 kW electric power input. This is quite small compared with the 100 K reported in the literature [5–7]. If the electric power is 3.6 kW, the temperature difference is less than 12 K. Generally, the temperature distribution along the regenerator is linear, which means that the temperature at the middle point of the regenerator should be 186.5 K in this experiment. Fig. 6 shows that the average temperature of the four thermometers is obviously higher and increases with the electric power. This indicates that the temperature of the regenerator's hot end is much higher than 293 K or the cold end is higher than 80 K. The heat transfer in the heat exchangers needs further investigation [14–16].

4. Conclusions

This paper analyzed the effect of the regenerator and pulse tube length on the efficiency of a pulse tube cryocooler. It is concluded that a change in the regenerator's length in a certain range has little effect on the efficiency although there is an optimum length that provides the maximum efficiency. The pulse tube affects the efficiency even less than the regenerator as long as the inertance tube can offer the ideal impedance. On this basis, a coaxial pulse tube cryocooler with especially lengthened regenerator and pulse tube was set up. Even though the regenerator was not packed with any high thermal conductivity fillings, a fairly homogeneous temperature distribution was obtained. At a cooling temperature of 80 K, the cryocooler can offer 520 W of cooling power

corresponding to a relative Carnot efficiency of 18.2%. When the cooling power was 285 W, the efficiency reached 21%.

Acknowledgements

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